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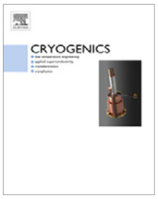

Effect of heat transfer on the performance of thermoelectric generator-driven thermoelectric refrigerator system

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ABSTRACT

A model of thermoelectric generator-driven thermoelectric refrigerator with external heat transfer is proposed. The performance of the combined thermoelectric refrigerator device obeying Newton's heat transfer law is analyzed using the combination of finite time thermodynamics and non-equilibrium thermodynamics. Two analytical formulae for cooling load vs. working electrical current, and the coefficient of performance (COP) vs. working electrical current, are derived. For a fixed total heat transfer surface area of four heat exchangers, the allocations of the heat transfer surface area among the four heat exchangers are optimized for maximizing the cooling load and the coefficient of performance (COP) of the combined thermoelectric refrigerator device. For a fixed total number of thermoelectric elements, the ratio of number of thermoelectric elements of the generator to the total number of thermoelectric elements is also optimized for maximizing both the cooling load and the COP of the combined thermoelectric refrigerator device. The influences of thermoelectric element allocation and heat transfer area allocation are analyzed by detailed numerical examples. Optimum working electrical current for maximum cooling load and COP at different total number of thermoelectric elements and different total heat transfer area are obtained, respectively.

1. Introduction

Semiconductor thermoelectric power generation, based on the Seebeck effect, and semiconductor thermoelectric cooling, based on the Peltier effect, have very interesting capabilities with respect to conventional power generation and cooling systems [1–3]. The absence of moving components results in an increase of reliability, a reduction of maintenance, and an increase of system life; the modularity allows for application in a wide-scale range without significant losses in performance; the absence of a working fluid avoids environmental dangerous leakage; and the noise reduction appears also to be an important feature. Thermoelectric generator and refrigerator have been used in military, aerospace, instrument, and industrial or commercial products, as a power generation or cooling devices for specific purposes. Many researchers are concerned about the physical properties of thermoelectric material and the manufacturing technique of thermoelectric modules. In addition to the improvement of the thermoelectric material and module, the system analysis and optimization of thermoelectric generator and refrigerator are equally important in designing high-performance thermoelectric generators and refrigerators.

In general, the conventional non-equilibrium thermodynamics [1,4] is used to analyze the performance of single-stage one- or multiple-element thermoelectric generators [5–13] and refrigerators [14–25]. Non-equilibrium thermodynamics is a progress of classical thermodynamics, it considers some specific phenomena such as Seebeck effect and Peltier effect. All objects of these researches are independent thermoelectric devices, that is, they generate direct-current power source for users (thermoelectric generator) or need a direct-current power source to provide direct current (thermoelectric refrigerator). In some special fields, the heat rejected from the thermal machine may drive a thermoelectric refrigerator through the use of a thermoelectric generator, so that the thermoelectric refrigerator does not need an independent power source. Such a new system is different from the traditional thermoelectric systems merely consisting of a thermoelectric generator and a refrigerator. These systems dispense with complicated pipelines and heat insulation, so they can be used in many special fields such as aircraft and submarine. Chen et al. [26] and Khattab and El Shenawy [27] built a model of this kind of combined system, i.e. single-stage thermoelectric refrigerator driven by single-stage thermoelectric generator, and analyzed the performance of the device.

The theory of finite time thermodynamics or entropy generation minimization [28–35] is a powerful tool for performance analysis and optimization of practice thermodynamic processes and

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Nomenclature

A	coefficient of system stable working electrical current equation
F	heat transfer surface areas of heat exchanger
f	heat transfer surface area ratio
I	working electrical current (A)
K	thermal conductance of a semiconductor couple (W/K)
k	heat transfer coefficient of heat exchanger (W/K)
M	total number of thermoelectric elements pairs of whole device
m	number of thermoelectric elements pairs of thermoelectric generator
n	number of thermoelectric elements pairs of thermoelectric refrigerator
T	temperature (K)
Q	rate at which heat is transferred (W)
R	total internal electrical resistance of a semiconductor couple (Ω)
x	ratio of number of thermoelectric element pairs of the thermoelectric generator to total number of thermoelectric element pairs of the combined irreversible device

Greek symbols

α	Seebeck coefficients of P- and N- type semiconductor legs
ε	coefficient of performance (COP) of combined thermoelectric refrigerator device

Subscripts

1	parameter of thermoelectric generator
2	parameter of thermoelectric refrigerator
$H1$	heat source of thermoelectric generator
$H2$	heat sink of thermoelectric refrigerator
$L1$	heat sink of thermoelectric generator
$L2$	heat source of thermoelectric refrigerator
s	practical solution of working electrical current equation
opt	optimum parameter

devices. Finite time thermodynamics or entropy generation minimization is the method of modeling and optimization of various thermodynamic processes and devices that owe their thermodynamic imperfection to heat transfer, mass transfer, and fluid flow and other transport processes. It bridges the gaps not only between thermodynamic and heat transfer, mass transfer, fluid mechanics, and other transport science, but also between the physics and the engineering. It thermodynamically optimize performance of real finite-time and/or finite-size thermodynamic systems with the irreversibilities of heat transfer, fluid flow and mass transfer toward decreasing the irreversibility of the total system. Some authors have investigated the performance of thermoelectric generators [36–48] and thermoelectric refrigerator [49–57] using the combination of finite time thermodynamics and non-equilibrium thermodynamics. They analyzed the effect of finite-rate heat transfer between the thermoelectric device and its external heat reservoirs on the performance of single-element single-stage thermoelectric generators [36–43] and refrigerator [49–52]. They also investigated the characteristics of single-stage multi-element thermoelectric generators [44–48] and thermoelectric refrigerator [53–57] with the irreversibility of finite rate heat transfer, Joulean heat inside the thermoelectric device, and the heat leak through the thermoelectric couple leg. However, all of those were performed only for independent thermoelectric devices. There has been no investigation concerning the performance analysis and optimization for single-stage thermoelectric refrigerator driven by single-stage thermoelectric generator published in the open literature.

On the basis of the exo-reversible model of a single-stage thermoelectric refrigerator driven by a single-stage thermoelectric generator without external irreversibility built in Refs. [26,27], a model of thermoelectric generator-driven thermoelectric refrigerator with external heat transfer is built. The performance of the combined thermoelectric refrigerator device obeying Newton's heat transfer law is analyzed using the combination of finite time thermodynamics and non-equilibrium thermodynamics. Two analytical formulae for cooling load vs. working electrical current, and the coefficient of performance (COP) vs. working electrical current, are derived. For a fixed total heat transfer surface area of four heat exchangers, the allocations of the heat transfer surface area among the four heat exchangers are optimized for maximizing the cooling load and the coefficient of performance (COP) of the combined thermoelectric refrigerator device. For a fixed total number of thermoelectric elements, the ratio of number of thermoelectric elements of the generator to the total number of thermoelectric elements is also optimized for maximizing both the cooling load and the COP of the combined thermoelectric refrigerator device. The influences of thermoelectric element allocation and heat transfer area allocation are analyzed by detailed numerical examples. Optimum working electrical current for maximum cooling load and COP at different total number of thermoelectric elements and different total heat transfer area are given, respectively.

2. Model of a thermoelectric generator-driven thermoelectric refrigerator system

A schematic diagram of a thermoelectric generator-driven thermoelectric refrigerator device is shown in Fig. 1. The device consists of an irreversible single-stage multi-element thermoelectric generator and an irreversible single-stage multi-element thermoelectric refrigerator in series with internal and external irreversibilities. The direct-current power source of the refrigerator is the direct-current power output of the generator.

The irreversible thermoelectric generator is composed of m pairs of thermoelectric elements. Each element is composed of P-type and N-type semiconductor legs. The thermoelectric power generation element is assumed to be insulated, both electrically and thermally, from its surroundings, except at the junction-reservoir contacts. The internal irreversibility is caused by Joulean electrical resistive loss and heat conduction loss through the semiconductor between the hot and cold junctions. The Joulean loss generates an internal heat I^2R, where R is the total internal electrical resistance of the semiconductor couple and I is the electrical current generating from the semiconductor couple. The conduction heat loss is $K(T'_{H1} - T'_{L1})$, where K is the thermal conductance of the semiconductor couple, T'_{H1} is the hot junction temperature, and T'_{L1} is the cold junction temperature. Finite rate heat transfers, i.e. the temperature differences $(T_{H1} - T'_{H1})$ and $(T'_{L1} - T_{L1})$, where T_{H1} and T_{L1} are the temperatures of the heat source and heat sink of the thermoelectric generator, respectively, cause the external irreversibility. For the thermoelectric generator, the rate of heat transfer at the hot junction is Q_{H1}, and the rate of heat transfer at the cold junction is Q_{L1}.

The irreversible thermoelectric refrigerator is composed of n pairs of thermoelectric elements. Each element is composed of